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Wirelessly Interrogable Sensors for Different Purposes in Industrial Radio Channels

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Abstract - The radio request of passive wirelessly interrogable surface acoustic wave sensors is discussed. The parameters of the measurement process are divided to the contributions of the sensor, the radio channel and the radio request method. The measurement bandwidth and an example for an actual radio channel are discussed. For matching of the method to the measurement problem, the parameters of different radio request methods are estimated.

INTRODUCTION

To serve the growing demands of the industry for implementation of sensors to control the processes as much as possible, the need of sensor units is rising rapidly. In many applications, a wired connection between the sensor and the data processing system cannot be installed. The sensor may be in a separate room or a process chamber, pressure or radiation can inhibit a direct link. Then, a radio sensor system has to be established. Apart from active sensor units, surface acoustic wave devices, shortly discussed in the second chapter, came into use. They only consists of a passive SAW device, connected to an antenna. The sensors withstand a high rate of radiation and EMI. Taking proper materials for manufacturing, the devices are suitable to withstand severe environmental conditions. The radio link is set up via the radio channel. For periodically transmitting active devices, it has to be passed through one times. The passive sensors need an interrogation signal received via the channel, the response is retransmitted via the same. In the third chapter, the radio channel is discussed for the example of an actual radio channel between the interrogation antenna and the sensor unit. Then, in the fourth chapter, the methods of radio interrogation of passive SAW devices are compared by their parameters. A brief conclusion summarizes the contents of the paper.

SURFACE ACOUSTIC WAVE SENSORS

Surface acoustic wave (SAW) devices are well known for more than 30 years. Metallic structures (interdigital transducers, IDT) on the plain polished surface of a piezoelectric substrate are used for excitation of surface acoustic waves [1]. Applying the principle, a high number of devices for communication engineering can be built. Today, SAW components are implemented in almost every color TV set, in mobile communication systems, in remote control systems, etc. The electrical behavior of the devices can be designed to be insensitive against physical effects of the surroundings. Vice versa the component without compensation measures can be used for sensing. Since many years, SAW devices are implemented into the feedback loop of oscillator circuits and the change of output frequency is determined for measurements. One port SAW devices connected to an antenna can be operated as radio requestable passive sensors. The energy of a radio request signal is delayed in time and is retransmitted after the interrogating signal is switched of. Fig. 1 points out the principle of radio request of passive SAW sensors. The sensor types mostly used are SAW delay lines and resonators. Delay lines respond with a multiple delayed version of the interrogation signal. From the differential time

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delay, the measurand can be calculated. Sensors for identification, temperature, pressure, torque, etc. have been developed [2-4].

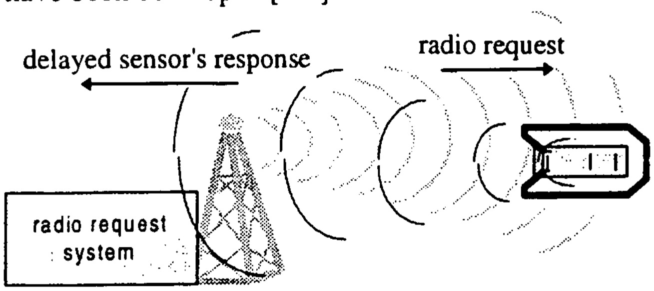

Fig. 1: Radio request of passive SAW sensors

Utilizing SAW resonators, the sensor is excited via a radio link and retransmits its response at its resonance frequency afterwards the stimulating signal have been turned off. No matter of sensor type, the measurand effects the propagation of the surface acoustic wave by mechanical extension or by change of the substrates parameters, changing the velocity of the SAW. The task of the sensor is to convert the measurand into an electrical parameter. Here, characteristic values are accuracy, cross sensitivity and bandwidth. Since the sensor is a crystal device, the accuracy is proportional to the reproducibility of the substrate material and the surface metallisation and to aging. SAW components for communication engineering are mass devices, this parameters can be predicted for the manufacturing process. An important parameter in sensor design is the cross sensitivity to other physical quantities, to temperature, acceleration, etc. In general, cross sensitivity effects mostly cannot be avoided, they have to coped with by differential measurements and proper signal processing methods.

The bandwidth of measurement depends on the bandwidth of the physical effect to the sensor element. The thermal capacity or the mechanical resonance frequency will limit the applicability for dynamic measurands. Therefore, temperature changes up to several Hz and mechanical vibrations up to a few kHz are feasible for measurement with directly effected SAW devices. The upper limit of the principle is given due to the time division method of radio request. In fig. 2 a sinusoidal variation of the measurand's effect ε to the sensor is sketched. Since the measurand effects a propagating SAW for a time interval ΔT, the error becomes

$$E \leq \frac{2\pi}{T_{period}/\Delta T}.$$

The error arises up to 30 percent, if the period of measurand is a tenth of the evaluated time delay. Therefore, the measurement bandwidth for actual sensors is approx. 100 kHz.

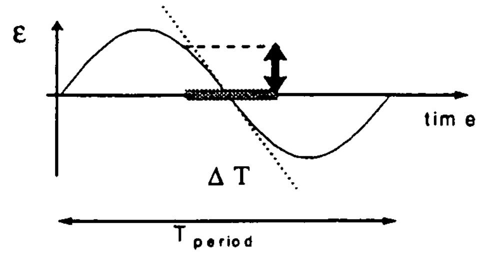

Fig. 2: Error estimation for dynamic measurand

A new method of passive sensing utilizing SAW devices is to vary the reflectivity in magnitude and phase by an external impedance connected to one of the reflectors of a reflective SAW delay line [. There, the SAW device operates as a delaying transponder, the sensor element is a conventional from stock sensor device. The cross sensitivities are reduced drastically due to the separation of sensor and transponder task. The upper measurement bandwidth is the product of the sensor's and the transponder's bandwidth. Since the maximum repetition rate of measurement is the inverse bandwidth of the transponder, the measurement's bandwidth can be estimated to be the RF bandwidth of the transponder, approx. 5 to 20 MHz.

Radio Channel

The task of the sensor is to collect the measurand with the required accuracy and bandwidth. Inseparable from this is the bidirectional radio transmission between interrogator and sensor unit.

The radio channel is characterized by a multipath scenario. The radio request signal propagates from the interrogation antenna to the sensor antenna via a number of paths. The response signal is received via multiple paths too. In time domain, one interrogation impulse is received at the sensor as a spread train of impulses. In frequency domain, the (time variant) summation of the delayed RF signal components yields frequency selective interference at the receiving antenna. In communication engineering, statistical parameters like delay spread and coherence bandwidth are assigned to this signal. In fig. 3 the received RF signal of an interrogation channel is

drawn in time domain for one transmitted RF impulse.

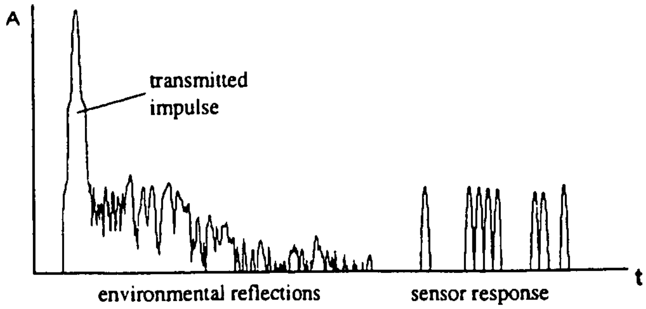

Fig. 3: Signal received during radio request

As seen in fig. 3, the delay of the SAW sensor has to be larger than the duration of the environmental echoes, determining the minimum size of the device. In usual low range radio channels for sensor request, due to the few dominant echoes from the radio channel, the coherence bandwidth, the bandwidth of the interferences remains small. To avoid signal loss, the bandwidth of radio request have to be larger than this, usually 1 MHz is sufficient. The reflections not only depend on fixed structures. The multipath scenario changes with time, with the sensor / interrogator locations and with moving things around. The interference fading is a statistical parameter.

For a moving sensor, the radio channel depends on the geometry of the setup. Due to the Radar principle, the attenuation increases with the fourth power of the distance. Additionally the coupling of the antennas depends on polarization, etc. The shadowing in sensor radio channels usually is a deterministic parameter and can be measured in magnitude and phase. In fig. 4, the magnitude of the transfer function of the radio channel is drawn for the radio link between an antenna at the chassis and one in the tire of a car, versus the wheel rotation angle.

It can be seen, that, because of shadowing from axles etc., for special rotation angles a transition of energy transmission from one dominant path to another occurs. An important parameter of the radio channel are the governmental limitations for bandwidth and radiated power. Therefore, the operation is limited to ISM bands only. A further restriction is the collected noise. The thermal noise for a bandwidth of 1 MHz is -114 dBm. Due to man made noise, the total noise interference is up to approx. -90 dBm for a 1 MHz bandwidth, limiting the sensitivity of the system.

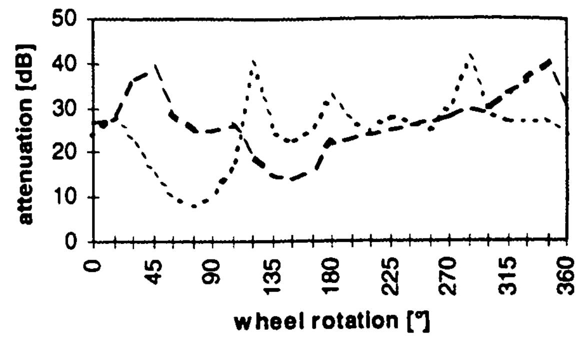

Fig. 4: Transfer function for a radio channel in a car versus the wheel rotation

The maximum allowed all inclusive attenuation is the difference (in dB) of transmitted energy and the minimum energy for detection with the admissible error rate. It is the sum of path loss and insertion loss of the sensor. Since the path loss is larger than $10 \cdot \log[(4\pi d/\lambda)^4]$ dB, it limits the distance range. The path loss is approx. 50 dB for a 433 MHz signal via a bidirectional channel with 1 m length. The actual insertion loss of delay lines is 12 to 40 dB. For mismatch etc. an additional loss of 10 dB can be calculated.

RADIO REQUEST METHODS

In the recent years, many radio request methods for passive SAW delay line and resonator sensors have been developed [6, 7]. For radio request, the method of time division is applied. Resonators and delay lines are excited with an RF signal. Then, the request system is switched to receive mode. For the signal processing, two fundamental principles are used:

- time domain processing (TDP)
- frequency domain processing (FDP)

The method widely applied, is the TDP for delay lines. An RF impulse is transmitted, the response is sampled and the measurand is calculated. The phase shift or the differential amplitude of two or more reflected signals is evaluated. For resonator interrogation, the TDP method performs a sampling of the decaying signal and a mean square error (MSE) fitting of the samples with parameter estimation. Methods to enhance the sensitivity and resolution of the TDP readout have been proposed [2]. TDP usually is a one shot method. The whole information about the sensor is gained within a

single response cycle. Therefore, a high rate sampling and signal processing is required. The method is suitable for high speed measurements up to the theoretical limits mentioned above. Since power and bandwidth are limited, the energy in the request signal is low (approx. 100 nWs = 20 dBmWs). Therefore, the received energy is e.g. [20-(50+20+10)]= -60 dBmWs. With a noise figure of up to 10 dB for a low cost system, the received energy to noise ratio E_b/N_0 is low (e.g. 20 dB) and the rate of errors arises to get useless for a distance larger than 2 m. Like for Radar systems, the range can be enhanced by coherent integration methods. The signal energy is enhanced by the factor of integration cycles, each noise contribution is statistically independent to the others. The total E_b/N_0 is increased, the achievable distance range is increased [3]. An improvement in range can be gained by impulse compression methods, but the processing gain remains low due to the low bandwidth allowed.

The FDP methods are very similar to the operation of a network analyzer for S11 measurement. The narrow band response of the device is measured wirelessly in magnitude and phase. The time response can be calculated by performing an inverse Fourier transform. A totally analog method for the interrogation of resonators is the method described in [7], where an oscillator is locked to the remote SAW resonator.

FDP methods are multi-shot measurements. The measurand is evaluated from a number of interrogation results. For one single request (at one frequency), only two sample points (magnitude and phase) have to be recorded. The signal processing can be done off-line, the speed requirements are less difficulty. It is not suitable for high speed measurements of dynamic measurands. The method includes the integration, simultaneously, the signal's energy for processing is high. The distance range is extended. Further, the bandwidth of the single transmitted signal is small. The resolution of the measurement can be enhanced by a trade-off with the duration of the total period by enhancement of the number of frequency points for interrogation. Usually, to perform the IFFT, the FDP methods require higher (but much slower) effort for signal processing than the TDP methods.

CONCLUSION

The parameters of the radio request of passive SAW sensors have been discussed. They can be divided to the properties of the sensors, the radio channel and the interrogation method. The sensor has to be optimized to collect the measurand with the proper accuracy and bandwidth. The radio channel actually is given by the surroundings, its parameters have to be took into consideration. The radio request method should be selected to yield a sufficient resolution without limiting the bandwidth and the accuracy of the total system. The TDP methods preferably are to be used for high speed, low distance range measurements. For higher distances and lower bandwidth of measurand, FDP methods help to reduce data processing speed. An optimization of radio request has to take into account all parameters and yields the preferable method for a specific measurement problem and the according radio channel.

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